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Today's View on Strangeness

John Ellis

CERN, CH-1211 Geneva 23, Switzerland

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Abstract. There are several different experimental indications, such as the pion-nucleon Σ term and polarized deep-inelastic scattering, which suggest that the nucleon wave function contains a hidden $s\bar{s}$ component. This is expected in chiral soliton models, which also predicted the existence of new exotic baryons that may recently have been observed. Another hint of hidden strangeness in the nucleon is provided by copious ϕ production in various $N\bar{N}$ annihilation channels, which may be due to evasions of the Okubo-Zweig-Iizuka rule. One way to probe the possible polarization of hidden $s\bar{s}$ pairs in the nucleon may be via Λ polarization in deep-inelastic scattering.

PACS. 12.39.Dc Skyrmions – 13.75.Cs Nucleon-nucleon interactions – 14.20.-c Baryons

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1 How Strange is the Nucleon?

Some people might argue that this is a "strange" question: why should the nucleon be strange at all - after all, is it not just made out of three up and down quarks? We should not jump to such a naïve conclusion. For a start, even the vacuum is strange: chiral symmetry for π, K mesons tells us that [1]

$$< 0|\bar{s}s|0 >= (0.8 \pm 0.1) < 0|\bar{q}q|0 > .$$

This hidden strangeness cannot be expected to disappear when one inserts a set of three quark 'coloured test charges' into the vacuum. Moreover, hidden strangeness will be generated in perturbative QCD:

$$\text{quark} \rightarrow \text{gluon} \rightarrow \bar{s}s\,\text{pair}.$$

There are also non-perturbative mechanisms for generating $\bar{s}s$ pairs in the nucleon, such as instanton effects [2].

Another objection to this 'strange' question is the fact that (at least some) experiments do not see very much strangeness in the nucleon. For example, CCFR measures a strange momentum fraction: $P_s = 4\%$ at $Q^2 = 20\mathrm{GeV}^2$ [3], the HAPPEX measurement of a combination of strange electric and magnetic form factors gives a small value: $G_E{+}0.39G_M = 0.025{\pm}0.020{\pm}0.014$ at $Q^2 = 0.48\mathrm{GeV}^2$ [4], SAMPLE finds a small strange contribution to the nucleon magnetic moment: $-0.1 \pm 5.1\%$ [5], and the A4 Collaboration finds small strange contribution to another combination of form factors: $G_E + 0.225G_M = 0.039 \pm 0.034$ [6].

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On the other hand, a few experiments indicate quite large matrix elements for some hidden-strangeness operators. One prominent example is the π-nucleon Σ term, whose value is related to the strange scalar density:

$$y = \frac{2 < p|\bar{s}s|p >}{< p|\bar{u}u|p > + < p|\bar{d}d|p >}.$$

Two recent determinations of the π-nucleon Σ term have found large values [7] :

$$\Sigma = 64 \pm 8,\ (79 \pm 7)\,\mathrm{MeV}$$

corresponding to large values of $y = 1 - \sigma_0/\Sigma$, where octet baryon mass differences give $\sigma_0 = 36{\pm}7$ MeV [8] and hence $y \sim 0.5$. Another example is the strange spin of the nucleon: a naïve interpretation of measurements of polarized deep-inelastic structure functions would yield [9]:

$$\Delta s = dx[s_\uparrow(x) - s_\downarrow(x) + \bar{s}_\uparrow(x) - \bar{s}_\downarrow(x)] = -0.10 \pm 0.02.$$

On the other hand, HERMES measurements of single-particle inclusive particle production have been interpreted as indicating that [10]

$$\Delta s = dx[s_\uparrow(x) - s_\downarrow(x) + \bar{s}_\uparrow(x) - \bar{s}_\downarrow(x)] = 0.03 \pm 0.03 \pm 0.01.$$

However, this estimate has been questioned on the grounds that corrections to independent fragmentation may be large [11]. The overall picture is that hidden-strangeness matrix elements in the nucleon may be small or large, depending on the J^{PC} quantum numbers carried by the $\bar{s}s$ pair, which is quite compatible with theoretical ideas [12].

Even if one accepts the first estimate of Δs, there has been an argument about its interpretation, based on the observation that in one regularization scheme Δs gets a large contribution from gluons Δg: $\tilde{\Delta s} = \Delta s - (\alpha_s/\pi)\Delta g$:

perhaps the 'bare' Δs vanishes, and Δg is large and positive [13]? Since the Δg correction is scheme-dependent, one may wonder how well defined it is [14]. However, this suggestion has at least raised the profile of the interesting question how large Δg may be. A first measurement of the gluon polarization was reported by FNAL experiment E581/704 [15], measuring π^0 production at high p_T, and Fig. 1 shows recent measurements of ΔG. HERMES find [16]

$$< \Delta G/G >= 0.41 \pm 0.18\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

for $0.06 < x_G < 0.28$, and the SMC finds [17]

$$\Delta G/G = -0.20 \pm 0.28 \pm 0.10$$

for an average longitudinal momentum fraction $< \eta \equiv x_G(1 + \hat{s}/Q^2) >= 0.07$ using the asymmetry in hadron-pair production at high p_T. Most recently, COMPASS has announced a new determination, again via the asymmetry in hadron-pair production at high p_T [18]:

$$\Delta G/G = 0.06 \pm 0.31 \pm 0.06 \tag{1}$$

at an average $< x_G >= 0.13$, and PHENIX is preparing a new determination via the double helicity asymmetry in $pp \to \pi^0$ at high p_T. However, all these measurements have large uncertainties, both systematic and statistical. For the time being, there is no strong indication that ΔG is large, and even its sign must still be regarded as an open question.

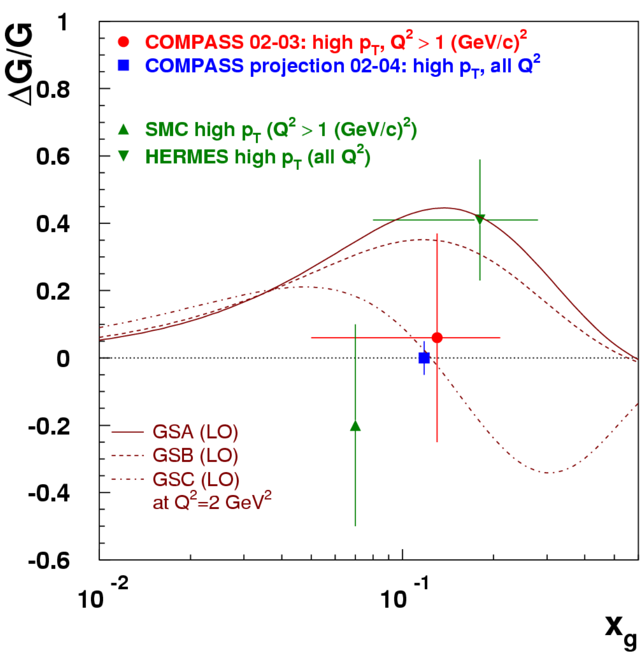

Fig. 1. Comparison of recent determinations of ΔG by HERMES [16], SMC [17] and COMPASS [18].

2 Models of the Nucleon

In the last millennium, the naïve quark model (NQM) [19] held pride of place. It envisages the nucleon as composed of three constituent quarks Q, each with mass $M_Q \sim 300$ MeV, in a non-relativistic wave function. Any additional $q\bar{q}$ pairs are thought to be generated perturbatively, and few of them are expected to be $s\bar{s}$ pairs. Baryons sit in the usual non-exotic SU(3) multiplets, and the combination of a UUD or UDD wave function with meagre pair creation explains the Okubo-Zweig-Iizuka (OZI) rule [20]. The proton spin is simply the algebraic sum of valence constituent-quark spins, which add up to 1/2.

Chiral soliton models [21] provide an alternative viewpoint for the new millennium. They are based on the observation that the intrinsic masses of the (current) quarks defined at short distances are much smaller: $m_{u,d} \sim$ few MeV, $m_s \sim 100$ MeV. Hence the quarks should be treated relativistically, and there are many intrinsic $q\bar{q}$ pairs in the nucleon wave function, which are treated as clouds of meson fields. In this picture, low-lying exotic SU(3) multiplets are predicted [22], as are evasions of the OZI rule due to the copious $s\bar{s}$ pairs in the nucleon. Moreover, the nucleon spin is obtained from orbital angular momentum, the sum of the quark spins vanishes in the limit of vanishing quark masses and a large number of colours, and the $s\bar{s}$ pairs are polarized [23].

In the chiral soliton model, baryons are constructed as clouds of π, K, and η_8 mesons, and the presence of the latter is one way to understand the copious $s\bar{s}$ pairs in the baryon wave function. Exotic baryons are expected as excitations of the meson cloud with non-trivial SU(3) transformation properties, which can also be interpreted as excitations of the $q\bar{q}$ sea in the baryon. The baryon spin is due to the coherent rotation of this meson cloud, motivating the interpretation of the baryon spin as orbital angular momentum, and requiring the $s\bar{s}$ pairs to be polarized.

Specifically, in the limit of massless quarks and a large number of colours, the meson cloud contains no SU(3) flavour-singlet η_0 mesons, and nor do the π, K, and η_8 mesons present have any coupling to the η_0. Since axial-current matrix elements are related in the chiral limit to pseudoscalar-meson couplings, the absence of the η_0 implies that the SU(3)-singlet axial-current matrix element between baryons also vanishes. Classically, this matrix element is in turn related to the sum of the quark spins in the baryon, which therefore vanishes. Since the sum of the u and d quark contributions to the proton spin is positive and does not vanish, there must be a negative, non-zero strange contribution that cancels them [23].

The presence of a non-trivial $q\bar{q}$ sea in the nucleon suggests that there may exist baryons with 'exotic' quantum numbers that cannot be explained in terms of naïve three-quark wave functions. It is surely too naïve to imagine that, if one places three quarks in a vacuum containing many $q\bar{q}$ pairs, there will never be any rearrangement of the $q\bar{q}$ quantum numbers. If the $q\bar{q}$ quantum numbers do not cancel each other out exactly, the resulting baryonic state will have 'exotic' quantum numbers. In the chiral-

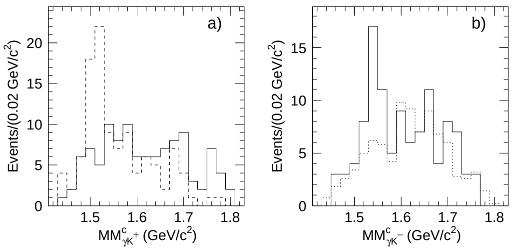

Fig. 2. The left panel shows that the $\Lambda(1520)$ signal can be isolated with suitable cuts. The signal for the exotic baryon Θ^+ is the solid histogram in the right panel, and the dashed histogram is a control sample [25].

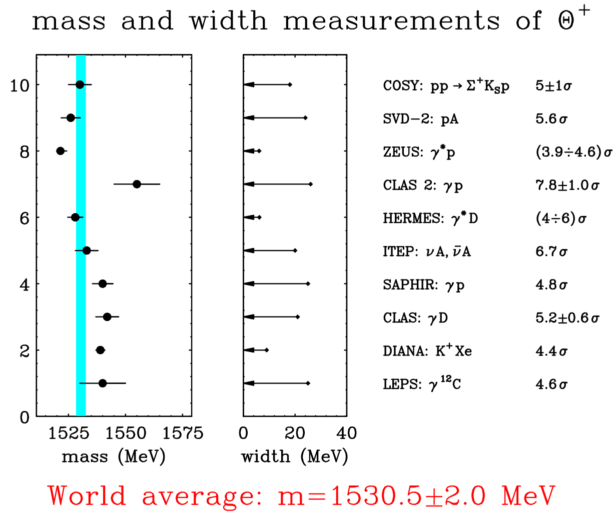

Fig. 3. Compilation of measurements of the Θ mass and decay width [28].

soliton language, these can be thought of as excitations of the meson cloud.

This line of argument led theorists working on chiral solitons to predict the existence of a relatively light antidecuplet of exotic baryons [22], resembling 'pentaquark' states in the NQM, of which the lowest-lying member would have $udud\bar{s}$ quantum numbers and weigh about 1530 MeV [24]. On the other hand, the Particle Data Group quoted in 1987 "...the prejudice against baryons not made of three quarks ...", and ceased to consider their existence.

This changed with the report by the LEPS Collaboration at Spring-8 [25] of a candidate exotic baryon with $udud\bar{s}$ quantum numbers and weighing about 1540 MeV, shown in Fig. 2. This was soon followed by an avalanche of corroborating evidence from other experiments [26], which stimulated considerable theoretical enthusiasm. However, these observations are somewhat problematic. The masses vary outside the quoted statistical and systematic errors, as seen in Fig. 3, with peaks in nK^+ final states tending to be heavier than those in pK^0 final states [27]. Moreover, KN partial-wave analyses require the decay width to be < 1 MeV [29]: this is surprisingly narrow, and some experiments have reported widths close to their experimental mass resolutions, as also seen in Fig. 3.

Nevertheless, the striking evidence in favour of the early chiral-soliton predictions motivated revisiting them [30]. It was soon realized that the accuracy of the mass prediction [24] was somewhat fortuitous, as it was based on a debatable assignment of another member of the baryon antidecuplet, and the mass splittings within this multiplet were calculated using an outdated value for the π-nucleon Σ term. Using plausible ranges for the chiral soliton moments of inertia that control the mean excitation energy of antidecuplet baryons, and the more modern value of the Σ term discussed above, there is an uncertainty in the θ^+ baryon mass of at least 100 MeV. As for the decay width, although it vanishes in the limit of a large number of colours [31], leading-order calculations with plausible baryon couplings had difficulty in pushing the decay width below about 10 MeV. We made a detailed study of SU(3)-symmetry breaking effects on baryon-meson couplings in chiral soliton models, finding values of the π-Nucleon and $\pi - \Delta$ couplings that are consistent with experiment, as seen in Fig. 4. These effects tend to reduce further the θ^+ decay rate, as seen in Fig. 5, though a width < 1 MeV still seems unlikely [30]. One of the key predictions of chiral soliton models is the existence of other, more 'exotic' baryon multiplets, such as a 27 and a 35 of SU(3) that are slightly heavier than the antidecuplet. In particular, there should be a θ^{++} state weighing < 100 MeV more than the θ^+, as seen in Fig. 6. It is difficult to understand how such a state could have escaped observation in many experiments, but CLAS data may hint at the existence of such a state [32].

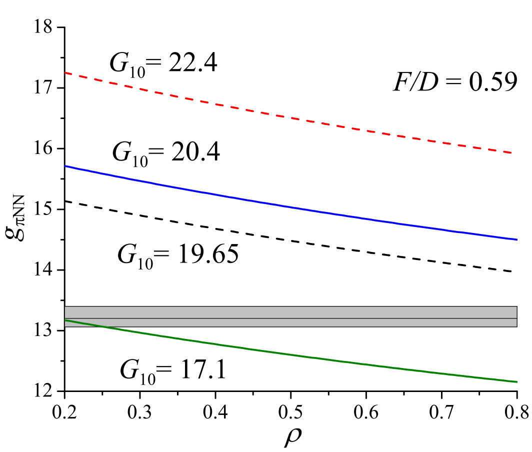

Fig. 4. Chiral-soliton calculations of the π-nucleon coupling depend on the model parameters G_{10} and ρ, but may be consistent with experiment (shaded) [30].

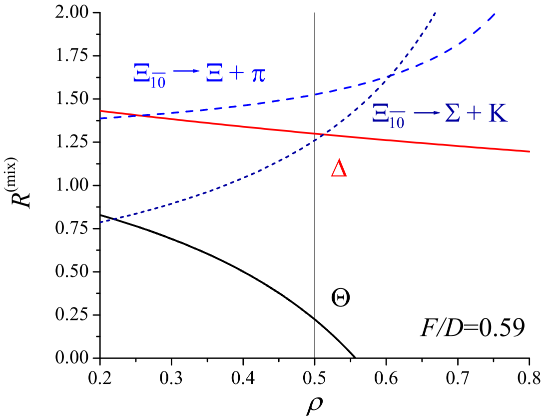

Fig. 5. Corrections to the Θ coupling tend to reduce its decay width, whereas the decays of other antidecuplet baryons are not strongly suppressed [30].

What would be the implications of 'exotic' baryons for our understanding of strangeness in the nucleon? As has already been mentioned, the exotic baryon spectrum is sensitive to the value of the π-N Σ term. Using the chiral soliton mass formula

$$\frac{m_s}{m}\,\Sigma = \underbrace{3(4M_\Sigma - 3M_\Lambda - M_N)}_{octet} + \underbrace{4(M_\Omega - M_\Delta)}_{decuplet}$$
$$- \underbrace{-4(M_{\Xi 3/2} - M_{\Theta^+})}_{antidecuplet}$$

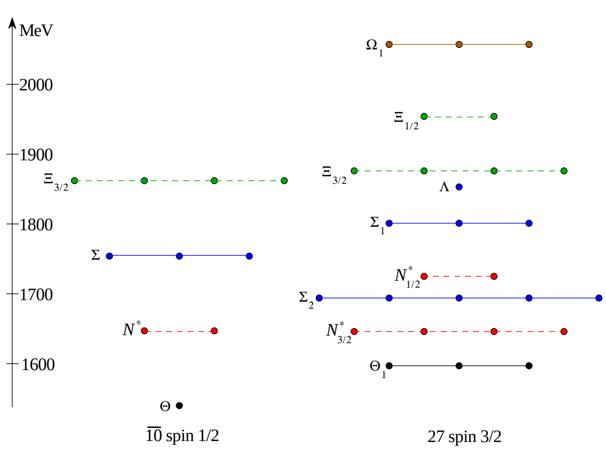

Fig. 6. Spectroscopy of the lowest-lying exotic baryons predicted in chiral-soliton models [30].

the observation of the Ξ^{--} baryon reported by NA49 [33], if confirmed, would correspond to

$$y = 2 \cdot \frac{< N|s\bar{s}|N >}{< N|u\bar{u} + d\bar{d}|N >} \approx 0.6.$$

This is quite consistent with the direct measurements of the π-N Σ term discussed earlier [7], perhaps lending some credence to the whole chiral soliton scheme.

3 OZI Violation or Evasion?

The Okubo-Zweig-Iizuka (OZI) rule is based on the idea that processes with disconnected quark lines are suppressed. As a corollary, it is not possible to produce $s\bar{s}$ mesons in the interactions of non-strange particles. Hence, ϕ meson production should be due only to the admixture of light quarks in the ϕ wave function, which is small, since the ϕ and ω mesons are almost ideally mixed. Generically, one would expect a production ratio

$$R(\phi/\omega) = \tan^2(\theta - \theta_I) = 4.2 \times 10^{-3}.$$

This is not very different from the weighted averages of experimental data from πN collisions:

$$R(\phi/\omega) = (3.30 \pm 0.34) \times 10^{-3}.$$

The corresponding ratios in NN collisions

$$R(\phi/\omega) = (12.78 \pm 0.34) \times 10^{-3}$$

and NN collisions

$$R(\phi/\omega) = (14.55 \pm 1.92) \times 10^{-3}$$

are somewhat larger, but not dramatically big.

On the other hand, there are large deviations from the naïve OZI relation in data from LEAR experiments on $p\bar{p}$ annihilations, particularly in the following reactions: $p\bar{p} \to \gamma\phi$, $p\bar{p} \to \pi\phi$ from the $^3S_1$ state, and $\bar{p}d \to \phi n$, as seen in Fig. 7 [34]. Moreover, the ϕ/ω ratio depends strongly on the initial-state spins of the nucleons and antinucleons, on their orbital angular momenta, on the momentum transfer and on the isospin. For example, the partial-wave dependence of annihilations into $\phi\pi$ is shown in Fig. 8, where we see that s-wave annihilations dominate. Another example of a large ϕ/ω ratio is in the Pontecorvo reaction $\bar{p}d \to \phi n$ shown in Fig. 9, where it is compared with the annihilation process $\bar{p}d \to \pi^0 n$.

The OZI rule could be evaded if there are $s\bar{s}$ pairs in the nucleon wave function, since new classes of connected quark diagrams could be drawn for the production of the ϕ and other $s\bar{s}$ mesons. Motivated by the data on polarized deep-inelastic scattering [35], we have formulated a polarized intrinsic strange- ness model [36,37], in which the $s\bar{s}$ pairs in the nucleon are assumed to have negative polarization, and to be in a relative 0^{++} state, not a 1^{--} state as in the naïve ϕ wave function. The production of strangeonium states may occur via rearrangement of the s

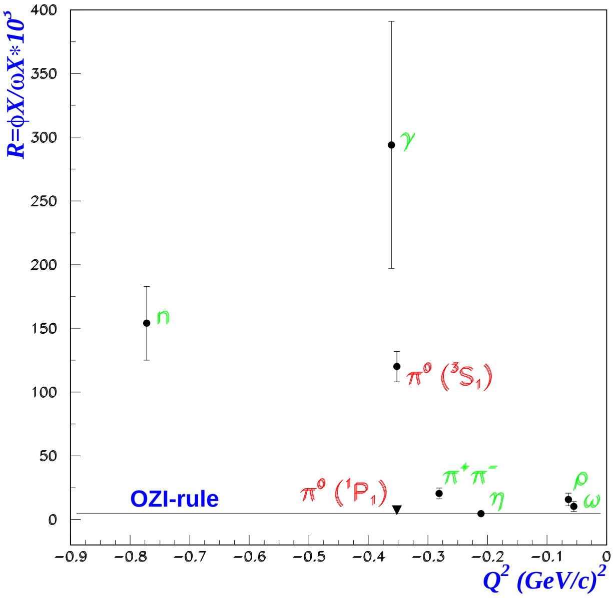

Fig. 7. The ratios of ϕ and ω production in association with various other particles in $N\bar{N}$ annihilation, as measured at LEAR [34], often exceed predictions based on the naïve OZI rule.

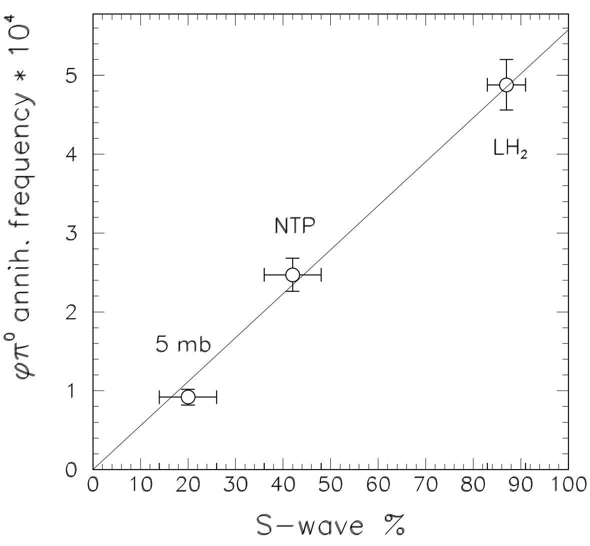

Fig. 8. The annihilation $p\bar{p} \rightarrow \phi\pi^0$ proceeds predominantly via the s wave [34].

and $\bar{s}$ in different nucleons, and not via shake-out from an individual nucleon. Thus, *both* nucleons participate in the production mechanism, and their relative polarization and orbital angular momentum states are important. In particular, one would expect the ϕ and the $f_2'(1525)$ mesons to be produced more copiously from spin-triplet initial states than from spin-singlet initial states, the ϕ meson to be produced preferentially from $L = 0$ states, and the $f_2'(1525)$ to be produced preferentially from $L = 1$ states.

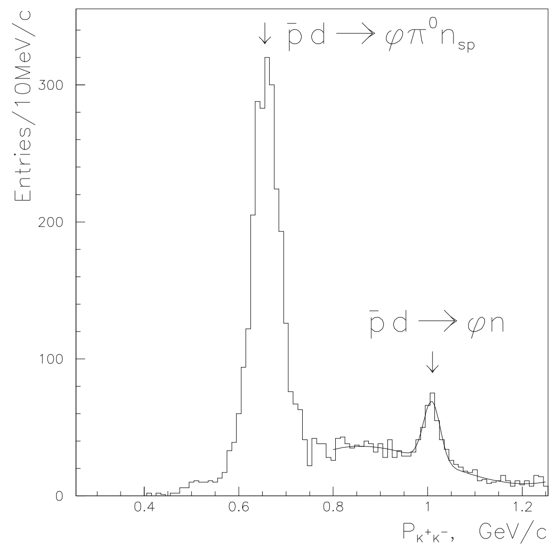

Fig. 9. Signal for the Pontecorvo reaction $\bar{p}d \rightarrow n\phi$ [34].

This model has led to several correct predictions [34]. In nucleon-antinucleon annihilations, the $p\bar{p} \rightarrow \pi^0\phi$ rates from the $^3S_1$ and $^1P_1$ initial states are in a ratio $\sim 15:1$, in agreement with the prediction of $L = 0$ dominance. On the other hand, the $p\bar{p} \rightarrow f_2'\pi^0$ rates are in a ratio $\sim 1:10$, in agreement with the prediction of $L = 1$ dominance. Moreover, there is evidence that the mechanisms for ϕ and ω production are different: the $^1P_1$ fractions in $\pi\phi^0$ and $\omega\pi^0$ are $< 7\%$ and $\sim 37\%$, respectively, and ϕ and ω production have different energy dependences in $n\bar{p}$ annihilations. Also, it has been observed that the initial states in $p\bar{p} \rightarrow \phi\phi$ are dominated by $J^{PC} = 2^{++}$, consistent with S-wave annihilations in a spin-triplet state. Additionally, spin-singlet initial states are strongly suppressed in $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$: the singlet fraction $F_s = (0.1 \pm 7.3) \times 10^{-3}$. The polarized-strangeness model is also consistent with the available data on the Pontecorvo reaction $\bar{p}d \rightarrow \phi n$ and on selection rules in $p\bar{p} \rightarrow K^*K^*$. Other successful predictions include 'OZI violation' in nucleon-nucleon scattering, where $p\bar{p} \rightarrow p\bar{p}\phi$ is about 14 times more copious than $p\bar{p} \rightarrow p\bar{p}\omega$ near threshold and the ϕ and ω angular distributions are different, the 'violation' of the naive OZI rule by a factor ~ 20 in $pd \rightarrow^3 H_e\phi(\omega)$, and the negative longitudinal polarization of Λ baryons measured in deep-inelastic neutrino scattering [38], discussed below.

However, there are also some serious problems for the polarized-strangeness model. For example, the strong OZI 'violation' in $\bar{p}p \rightarrow \gamma\phi$ takes place from a $^1S_0$ initial state, and the spin transfer D_{nn} in $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$ is small, whereas $K_{nn} > 0$, indicating that the spin of the proton is transferred to the $\bar{\Lambda}$, not to the Λ [39]. Moreover, CLAS data on the reaction $\boldsymbol{e}p \rightarrow e'K^+\Lambda$ indicate that the spins of the s and $\bar{s}$ are anti-aligned [40]. Also serious is the problem that $\bar{p}p \rightarrow \pi^0\phi$ is not possible from a $^3S_1$ initial state

without either flipping the spin of the s-quark or positive polarization of the strange quarks in the proton [41].

Many of these problems would be resolved if there are two components of polarized strangeness, one with $S_z = -1$ and one with $S_z = 0$ [42]. This would permit $p\bar{p} \to \gamma\phi$ and $p\bar{p} \to \pi^0\phi$ via rearrangement diagrams, and the CLAS data that require the spins of the s and $\bar{s}$ to be anti-aligned could be accommodated by shake-out of the $S_z = 0$ component. However, even this model does not fit all the data, as seen in the Table. One promising possibility is to assume the dominance of a spin-singlet us diquark configuration, as indicated in the last column of the Table [42]. Understanding the strange polarization of the proton is still a work in progress.

4 Probing Strangeness via Λ Polarization

Since the polarization of the Λ is measurable in its decays, and since the Λ polarization is inherited, at least in the naïve quark model, from its constituent s quark, Λ polarization is potentially a powerful way of probing polarized strangeness. Particularly interesting from this point of view is the measurement of Λ polarization in leptoproduction, where two options are available: measurements in the fragmentation region of the struck quark or in that of the target. The struck quark has net polarization, but is usually a u, so there is no interesting spin transfer to the Λ baryon. However, in the target fragmentation region the 'wounded nucleon' left behind by the polarized struck quark is itself polarized in general. A priori, it is a diquark system with the possibility of a polarized $s\bar{s}$ 'sea' attached to it. Memory of this polarization may be carried by the s and $\bar{s}$ in the wounded nucleon wave function and transferred to Λ and $\bar{\Lambda}$ baryons produced in the target fragmentation region [43].

We have modelled this idea using the Lund string fragmentation model incorporated in LEPTO 6.5.1 and JETSET 7.4, and have considered various combinations of two extreme cases in which the Λ baryon is produced by fragmentation of either the struck quark or the remnant diquark [44]. We then fix free parameters of the model by demanding consistency with data from NOMAD in deep-inelastic ν scattering [38]. In addition to providing a good fit to NOMAD data, as seen in Fig. 10, this procedure can be used directly to make predictions for electroproduction data from HERMES, and agrees very well. We have then gone on to make predictions for the COMPASS muon scattering experiment. COMPASS was originally conceived to measure the polarization of the gluons in the proton, but it may also be able to cast light on the polarization of the strange quarks!

5 Summary

As we have seen in this review, there are many pieces of experimental evidence for a significant amount of hidden strangeness in the proton wave function, notably the π-nucleon Σ term, polarized deep-inelastic scattering and

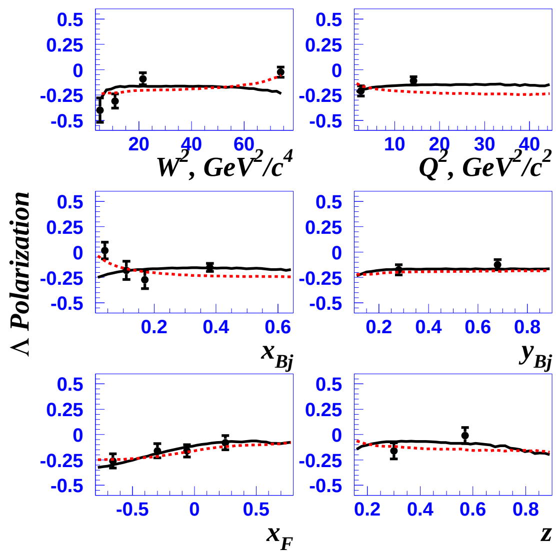

Fig. 10. Predictions for longitudinal Λ polarization in deep-inelastic scattering [44], compared with data from NOMAD [38].

large deviations from the naïve OZI rule. These observations may cast light on complementary models of nucleon structure, namely the 'naïve' quark model and chiral soliton models. The latter were recently boosted by reports of exotic baryons, whose existence was predicted years ago in the soliton model. Their spectroscopy depends, in particular, on the magnitude of the π-nucleon Σ term, and the tentative indication from the difference between the masses of the θ^+ and Ξ^{--}-baryons is that this should be large, in agreement with the latest direct determinations of this quantity. The situation with phenomenological models of OZI 'evasion' due to polarized $s\bar{s}$ pairs in the nucleon wave function is unclear: the data from LEAR and other low-energy experiments suggests that there must be many $s\bar{s}$ pairs, but their polarization states remain obscure. One thing is, however, clear: we may expect many more twists in the strange story of the nucleon!

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	$0^{++}: S_z = -1$	$0^{++}: S_z = -1, 0$	$0^{-+}: (us), (s\bar{s})$
$\phi\pi/\omega\pi$: large from $^3S_1$	+	-	+
$\phi\pi$: spin state	-	+	+
$\phi\gamma/\omega\gamma$: large from $^1S_1$	-	+	glueball
$\phi\eta/\omega\eta$: small from $^3S_1$	small Q^2	small Q^2	small Q^2
$\phi\rho/\omega\rho$: small from $^1S_1$	+	-	+
f_2'/f_2: large from p-wave	+	-	+
$\phi n/\omega n$: large	large Q^2	large Q^2	large Q^2
$P(\Lambda) < 0$ in DIS	+	+	+
$ep \to \Lambda K e : P(\Lambda)$	-	+	+
$\bar{p}p \to \Lambda\bar{\Lambda} : D_{nn}$	-	+	+/-
$\bar{p}p \to \Lambda\bar{\Lambda} : K_{nn}$	-	-	+
$pp \to pp\phi$: large from $^3S_1$	+	-	+

Table 1. Score card for various models of polarized strangeness in the nucleon wave function.

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